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Differential absorption lidar for water vapor isotopologues in the 1.98 µm spectral region: sensitivity analysis with respect to regional atmospheric variability

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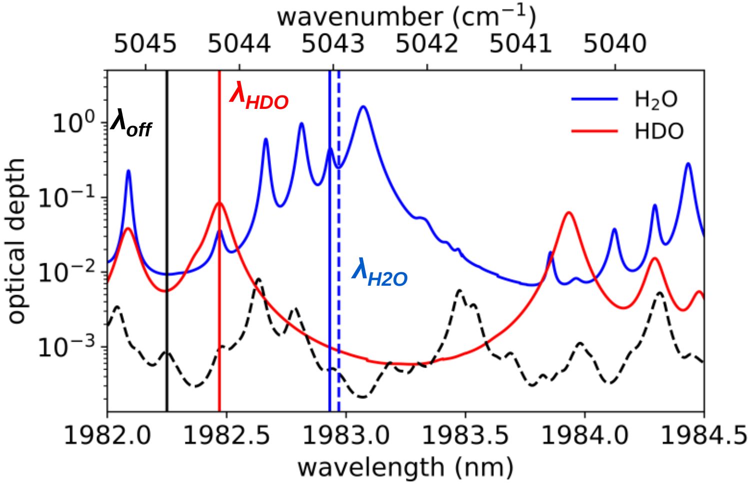
Introduction

Water Vapor and Isotope Lidar (WaVIL)

- Ground-based differential absorption lidar (DIAL) for water isotopologues **$H_2{}^{16}O$** and **$HD^{16}O$** in the lower troposphere (currently under development)
- Would allow the retrieval of vertical H_2O/HDO profiles and the isotopic ratio (HDO abundance in terms of δD)
- Can complement existing measurement methods (in-situ with CRDS, passive remote sensing)
- Operation wavelength: 1.98 µm
- Resolution: 150 m / 10 min

Project link: https://anr.fr/Project-ANR-16-CE01-0009



Optical depth over 1 km with uniform H_2O volume mixing ratio of 0.85% (15ºC, 1013.25 hPa, HITRAN 2016 spectroscopic database). Vertical lines indicate positions of off-line, HDO on-line, and H_2O on-line wavelengths.

Lidar setup

Key requirements for range-resolved DIAL:

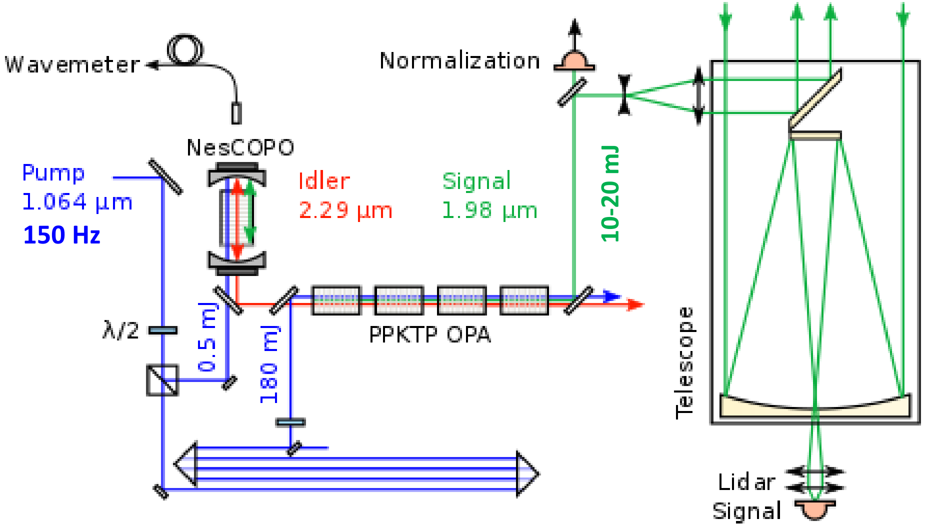
- Laser energies in the tens of mJ at 2 µm
- High detection sensitivity at 2 µm

Lidar transmitter:

- High-energy, single-frequency parametric source
- Approach: parametric conversion and amplification
  - nested cavity optical parametric oscillator (NesCOPO): pulsed, tunable source in the mid-IR
  - high-aperture PPKTP crystals: optical parametric amplification (OPA)

Lidar receiver:

- Cassegrain-type telescope (40 cm diameter)
- Detector: InGaAs pin photodiode (HgCdTe avalanche photodiode considered as an option in our simulations)



WaVIL instrument design: J. Hamperl et al. : WaVIL : A Differential Absorption LIDAR for Water Vapor and Isotope HDO Observation in the Lower Troposphere - Instrument Design. In Optical Sensors and Sensing Congress, paper LM4A.4; Optical Society of America, 2020; p LM4A.4, 2020

Previous demonstrations: E. Cadiou et al. : Multiple-species DIAL for H_2O, CO_2, and CH_4 remote sensing in the 1.98–2.30 µm spectral range. LACSEA Optical Society of America, 2018

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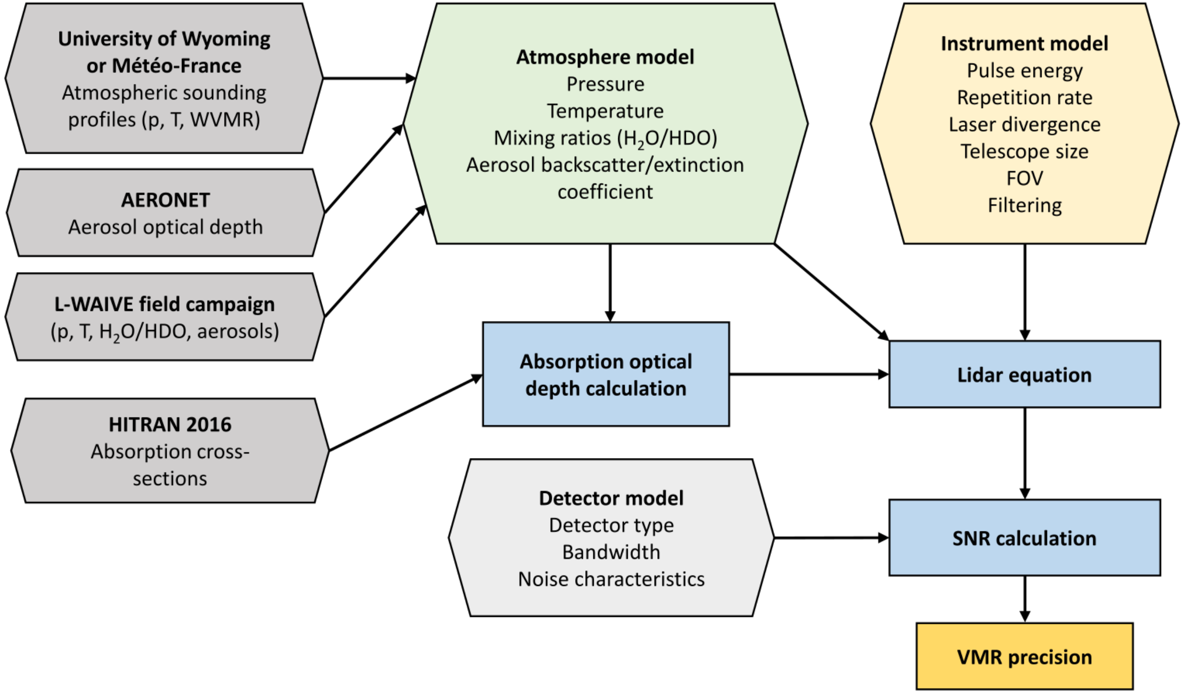
Lidar simulations



Simulation parameters

Instrument parameters:

Transmitter		Receiver		
Energy	10–20 mJ		i)	ii)
Pulse duration	10 ns	Telescope aperture	40 cm	40 cm
Repetition rate	150 Hz	Detector type	InGaAs PIN	HgCdTe APD
λ_{on} ($H_2{}^{16}O$) (1)	1982.93 nm	Detector diameter	300 µm	180 µm
λ_{on} ($H_2{}^{16}O$) (2)	1982.97 nm	Field of view (FOV)	630 µrad	380 µrad
λ_{on} ($HD^{16}O$)	1982.47 nm	Detector NEP	600 fW $Hz^{-1/2}$	75 fW $Hz^{-1/2}$
λ_{off}	1982.25 nm	Bandwidth	1 MHz	1 MHz
Divergence	270 µrad		Responsivity: 1.2 AW^{-1}	Quantum efficiency: 0.8
				Excess noise factor: 1.2

Atmospheric parameters:

- We used mid-latitude, tropic, and arctic model environments accounting for both vertical water vapor and aerosol variability. We constructed vertical profiles of aerosol extinction and backscatter coefficients constrained by the aerosol optical depth from the AERONET database for different locations (extrapolated to the 2 µm wavelength region).
- We also used vertical profiles of H_2O/HDO and aerosol extinction profiles obtained during a recent field campaign to demonstrate the potential of the lidar system.

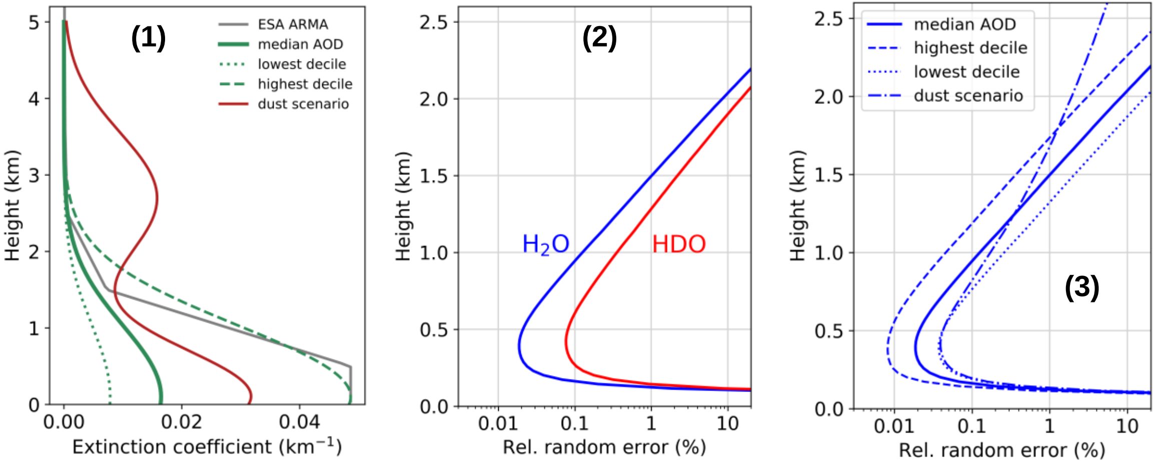
Simulation results: sensitivity to different environmental parameters

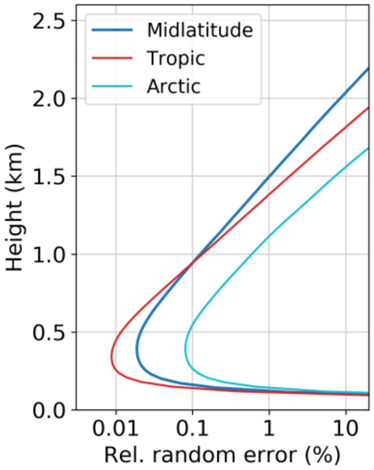
Example results for mid-latitude model (20 mJ laser energy, 10 min integration time, InGaAs PIN detector):

(1) Hypothetical aerosol extinction profiles assuming half-Gaussian distribution within the planetary boundary layer (PBL, <2 km) for different aerosol optical depths (AOD). Dust scenario incorporates elevated layer of aerosols on top of the PBL. Extinction profiles serve to calculate lidar backscatter coefficients.

(2) Relative random error (precision) on mixing ratios of H_2O and HDO for baseline atmospheric model (median AOD, average humidity)

(3) Precision on H_2O mixing ratio depending on different aerosol loads. Elevated dust gives rise to higher sensitivity above PBL.





Relative precision in H_2O VMR measurement for 3 baseline models

Achievable precisions vary by an order of magnitude between tropic (highest precision) and arctic (lowest) conditions.

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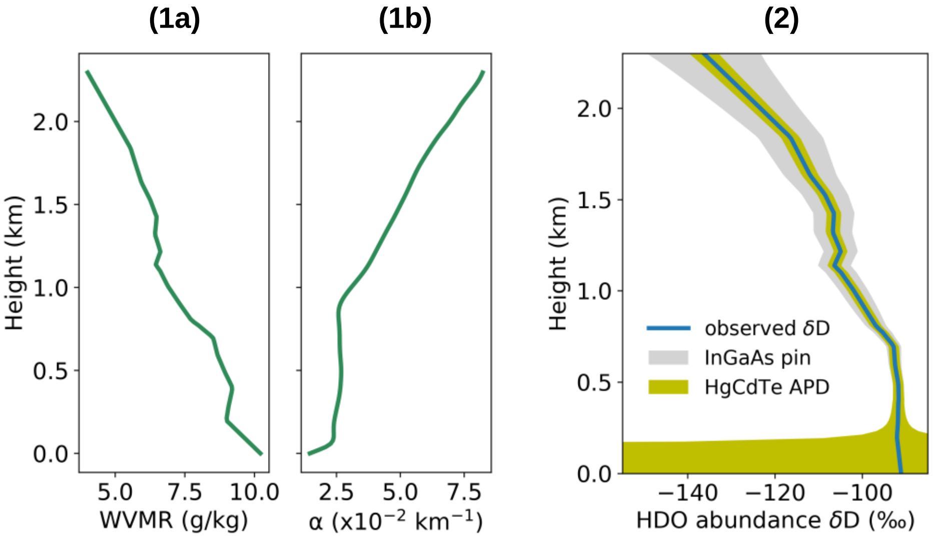
Simulation results: precision estimate using field campaign profiles

- We used water vapor mixing ratio profiles (1a) and columns of HDO abundance obtained during the recent L-WAIVE* field campaign to simulate the achievable precision with the WaVIL instrument
- Simulations also incorporate aerosol extinction/backscatter data (1b) measured by lidar (extrapolated to 2 µm using Angstrom exponent from sun-photometer products)
- As shown in (2), precisions achievable high enough to resolve vertical variations in HDO abundance
- Calculations based on: 20 mJ laser energy, 10 min integration time, 1 MHz bandwidth (150 m spatial resolution)



Profiles obtained during L-WAIVE field campaign serve as input for our lidar simulator

Calculated precision (shaded area, expressed as standard deviation) on HDO abundance for different detectors

*P. Chazette et al.: The Lacustrine-Water Vapor Isotope Inventory Experiment L-WAIVE. Atmospheric Chem. Phys. Discuss. Prepr., 1–43. doi:10.5194/acp-2020-1194, 2020.

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Conclusions

- **Water Vapor and Isotope Lidar (WaVIL)** under development for range-resolved measurements of the water vapor main isotope and its isotope HDO in the lower troposphere by differential absorption technique
- Isotope observations by lidar will enhance the comprehension of the water vapor budget and offer the potential to complement current in-situ observations
- Spectral range around 1.98 µm for addressing H_2O and HDO absorption lines
- Expected resolution: 150 m / 10 min
- Simulations indicate that relative random errors <1% on the H_2O VMR are achievable within the boundary layer (0-2 km)
- Sensitivity varies by one order of magnitude between tropic (highest precision) and arctic (lowest) atmospheric conditions
- By using H_2O/HDO profiles obtained during a field campaign we demonstrated the potential of the WaVIL instrument to deliver high-precision, range-resolved measurements of the isotopic ratio in terms of δD (few ‰)

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